DEEP REACTIVE-ION ETCHED MICRO VALVES FOR SPACECRAFT PROPULSION

William C. Tang, Indrani Chakraborty, and David Pyle
Jet Propulsion Laboratory
Center for Space Microelectronic Technology
MEMS Technology Group

ABSTRACT

We report on the design, fabrication, and test setup of a silicon diaphragm micro valve. The valve is designed to withstand temperature conditions typical in spacecraft propulsions while maintaining a low leak rate. Initial prototypes have been realized by using novel deep reactive-ion etching and bulk-micromachining techniques and metal-to-metal diffusion bonding. These will be tested to determine leak rates and possible flow rates.

INTRODUCTION

Space exploration in the coming millennium will be focused on developing rugged, low power micro-instruments suited for scientific payloads on miniature spacecraft. As one particular example, miniature chemical analyzers that can be used to look for evidence of once-in-existence life on other planets must be carried by micro-rovers weighing 1 kg or less. There are several key enabling technologies needed to realize ultra-miniaturized scientific instrument that can perform in-situ chemical analysis. Two of the most common analytical techniques, capillary zone electrophoresis and liquid or gas chromatography, require high performance valves with very low leak rate. In order to miniaturize these systems, several correspondingly small valves are needed that can be integrated with the rest of the systems.

At the same time, a miniaturized spacecraft also requires extremely small propulsion systems to perform ΔV and attitude control. A 10-kg class spacecraft, for example, requires thrust levels as low as 100 μN for fine orientation adjustment. Micro-propulsion engines that meet the power, size, and weight requirement are being developed, with the micro-valve being the most critical component.

During the current decade, there have been several silicon micromachined miniature valves reported in the field [1–5]. They are small, low power, and useful in a wide variety of applications. However, they are generally unsuitable for space applications. Most of these valves have leak rates that are still too high for miniature scientific payloads or micro-propulsion engines, which must retain their performance while idling several years on a launch pad and/or in space environment. Also, most are thermally actuated, limiting the temperature environments in which they can be used, which make them unsuitable for space applications with a wide temperature range.

The micro valve program at JPL was initiated specifically for space applications. The designs of these valves are being driven first and foremost by the need for an extremely low leak rate. Also, they need to survive the rigors of space flight, including high g-forces, shocks and thermal extremes. Finally, we need valves that can be used in chemistry experiments or propulsion systems without contaminating the reactants or being corroded by them.

Several microvalves are currently in development at JPL. In this paper, we will discuss one particular design, which will be used as a general-purpose valve/regulator for microfluidics applications.

DESIGN AND OPERATION

Larger, commercially available diaphragm valves inspire the design of this valve. A cross-sectional view is shown in Fig. 1a. The entire valve is 1.5 cm by 1.5 cm in area, and less than 0.2 cm tall. The fully packaged dimensions of a stand-alone device may be slightly larger.

The valve begins as three separate parts: the seat, the diaphragm, and the actuator. The seat contains the inlet and the outlet, as well as a set of seal rings around each opening on the topside. The diaphragm wafer has a circular corrugated diaphragm, with a circular boss in the center, covering both openings in the seat. Finally, the actuator consists of a piezoelectric disk in a rigid housing. All three parts are bonded together using a metal-to-metal diffusion bond.

The valve is normally closed. The piezoelectric stack is forced into a slightly contracted position during the bonding process in order to achieve a large sealing force on the two openings. Application of a voltage across the stack will cause it to contract even further, lifting the diaphragm away from the seat, as shown in Fig. 1b. This creates a channel between the two openings, allowing the passage of fluids.

Several design considerations have been implemented to target the requirements for space applications. The most important is a low leak rate. In order to achieve this, we apply a large sealing force to both the inlet and the outlet of the valve. Also, there is a large sealing area around both the inlet and the outlet, preventing leakage to the environment. This seal is implemented through metal-to-metal diffusion bonding, which typically yield satisfactory bonds, capable of comparably low leak rates as other techniques such as glass-metal seals or anodic bonding.

Finally, this device moves away from the typical thermal actuation found in most commercial-off-the-shelf (COTS) valves and instead uses a lead niobate piezoelectric disk. This approach enables a wide range of ambient operating temperature. The trade-off with piezoelectric actuation is that it requires high voltages in order to produce a substantial deflection. Design optimization and trade-off studies will be pursued rigorously once preliminary test data are collected.

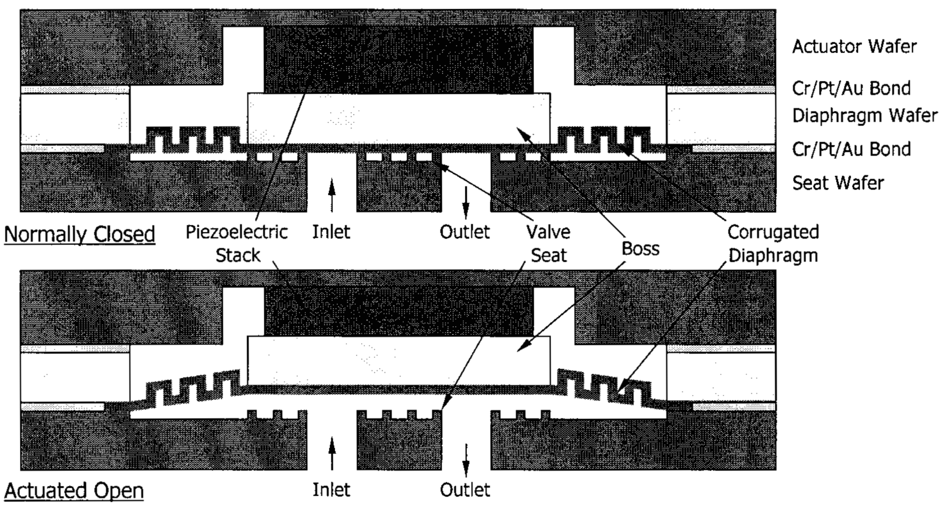

Figure 1. Cross sectional drawing of the valve assembly: (a) normally closed position and (b) actuated open position.

FABRICATION

The valve begins as three separate parts, the seat, the diaphragm, and the actuator. Presently, only seats and diaphragms have been fabricated and assembled. Once the seat-diaphragm assemblies are tested thoroughly, the design and implementation of the actuator will be performed.

Both pieces are bulk micromachined from n-type <100> silicon wafers. In order to create circular shapes, we use a novel deep trench reactive ion etch (RIE) technique [6]. This involves a series of alternating etching / passivation steps to achieve straight sidewalls in silicon irrespective of the crystal plane. The etching is done by a combination of SF_6 and O_2 gasses, and the passivation by a combination of C_4F_8 and O_2 gasses.

We also use a low-pressure chemical vapor deposition (LPCVD) system to deposit silicon nitride thin films to passivate the surfaces and to form the diaphragm. Finally, we use metal-to-metal diffusion bonding technique to assemble the parts. Both bonding surfaces are metalized with a Ti/Pt/Au layer. The metal is patterned and etched to create bonding surfaces. The parts are then held together under high temperature and high pressure creating a hermetic seal.

Figure 2 is the cross sectional drawings of the process flow. For the actuator, we intend to use a silicon housing with a lead niobate piezoelectric disk. Metalized via will need to be etched through the housing to make electrical contacts. This piece will also be bonded to the seat-diaphragm assembly through a metal-to-metal diffusion process. Figures 3 and 4 show the Scanning-Electron Microscope (SEM) pictures of the finished parts.

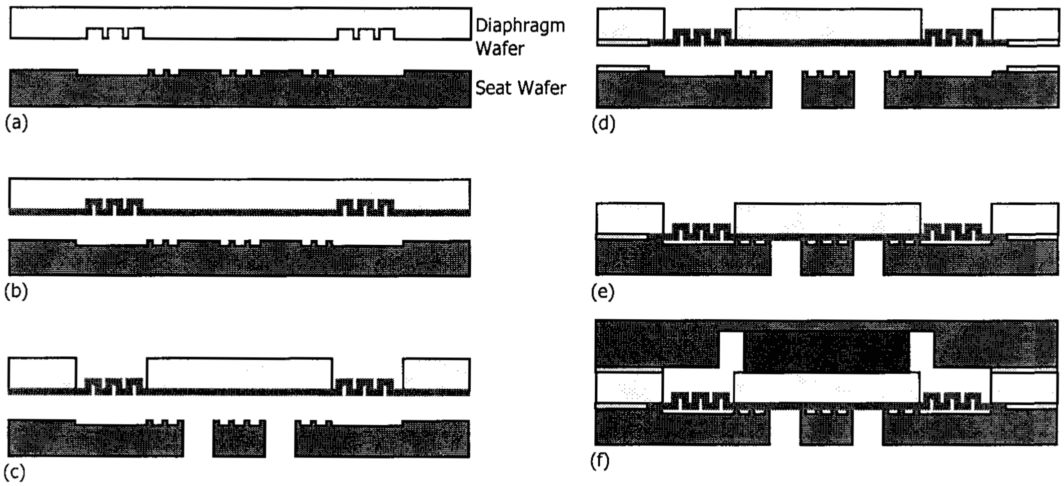

Figure 2. Fabrication process flow: (a) Pattern and etch 10 μm into both the Diaphragm and the Seat Wafers. (b) Deposit and pattern 0.5 μm low-stress silicon nitride by LPCVD on Diaphragm Wafer. (c) Pattern and etch 400 μm with DRIE to release diaphragm and form orifices. (d) Deposit and liftoff Cr (300 Å), Pt (300 Å), and Au (2500 Å) on both wafers. (e) Perform eutectic bond. (f) Repeat metallization and bonding for actuator wafer.

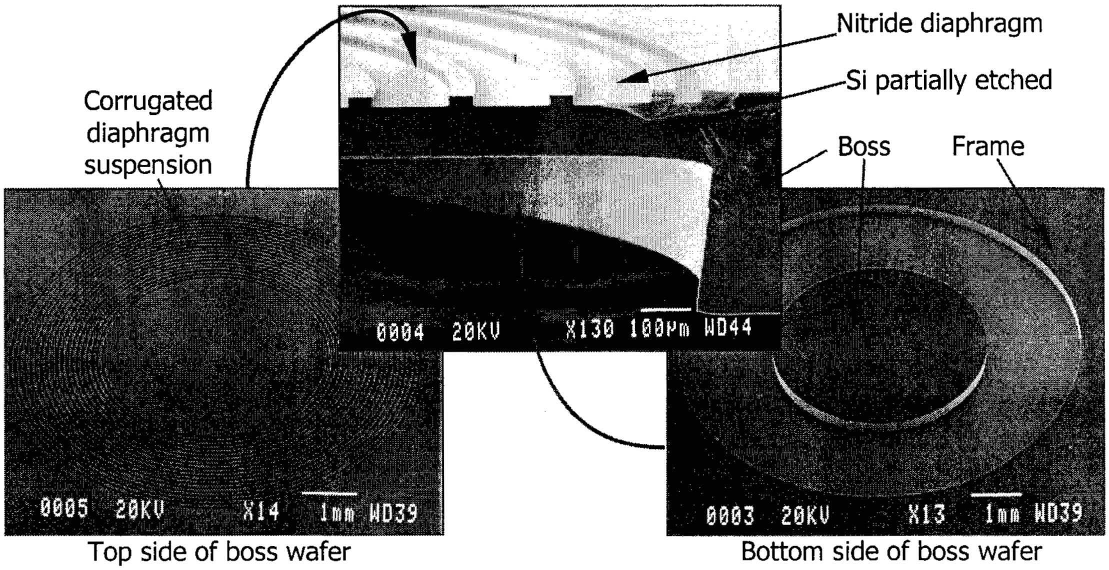

Figure 3. SEM pictures of valve boss and corrugated diaphragm.

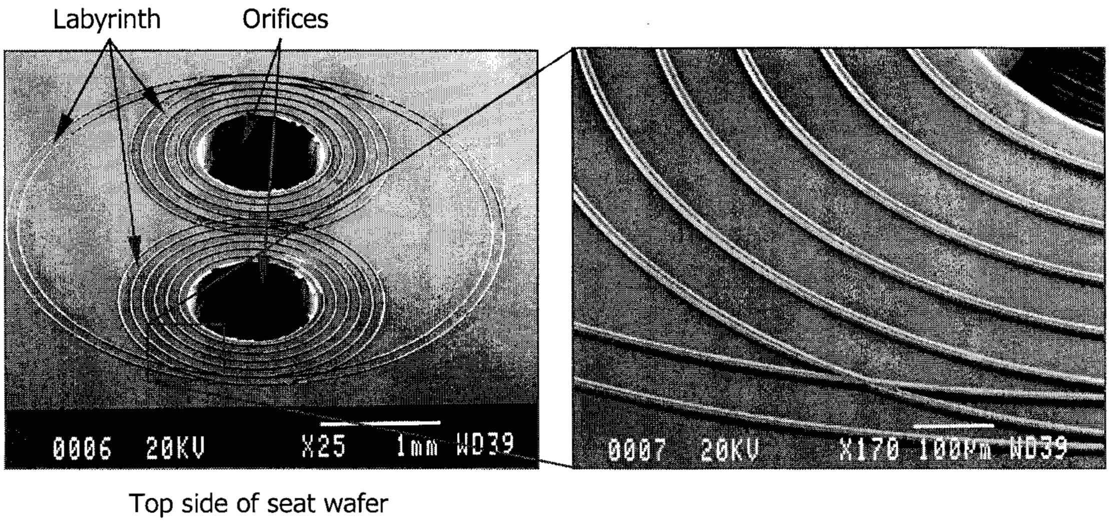

Figure 4. SEM pictures of valve seat.

TESTING

The first-generation prototype seat-diaphragm assemblies have been fabricated for leak testing. Several types of seal ring configurations have been implemented on these prototypes to determine an optimal configuration.

In order to completely characterize the valves, we will need to develop ways to accurately fixture them to very small tubes that can be attached to pressure lines, as well as pressure, temperature and mass flow sensors. These fixtures must then withstand the rigors of vibration, shock, and thermal testing while still maintaining a hermetic seal.

To do this, we are currently investigating a novel kovar, glass, and silicon anodic bonding technique. This technique may be used to attach the valves to small monolithic kovar pieces with precisely machined orifices running through them and attaching to tubes that can be connected to the necessary testing equipment. A schematic is given in Fig. 5. An anodic bond typically yields a hermetic seal, assuring that any leaks detected during testing are actually from the valve. Also, the bond should withstand much higher temperatures than traditional adhesives and sealant, allowing for rigorous thermal testing.

This kovar mount with the valve will then be fitted with a commercially available piezoelectric stack so that controlled forces can be applied to the boss. This entire assembly will be placed in an evacuated bell jar along with a mass spectrometer. Feedthroughs will supply helium to the free end of the kovar tube, a controlled voltage to the piezoelectric stack, and an output to monitor the mass spectrometer. When the helium supply line is pressurized, the opening in the bond allows for any gas that leaks out between the seat and the diaphragm to leak into the atmosphere and be detected by the mass spectrometer. From this test, we will produce data relating leak rate to force applied and inlet pressure applied, for each type of seal ring configuration.

Next, we will test valves for flow rates. In this case, the kovar piece will have two tubes for two valve openings. Similarly, this assembly will be placed in the fixture with the piezoelectric stack. Pressure and flow will be monitored both before the inlet and after the outlet to determine the pass-through performance of the valve. Also, we will determine whether or not this valve can be used as a regulator, and what possible design improvements are needed. A schematics is given in Fig. 5.

These tests will also give us valuable information on the necessary requirements for the actuator. Once these tests are done and the data analyzed, we can begin the optimized design for the integrated piezoelectric stack.

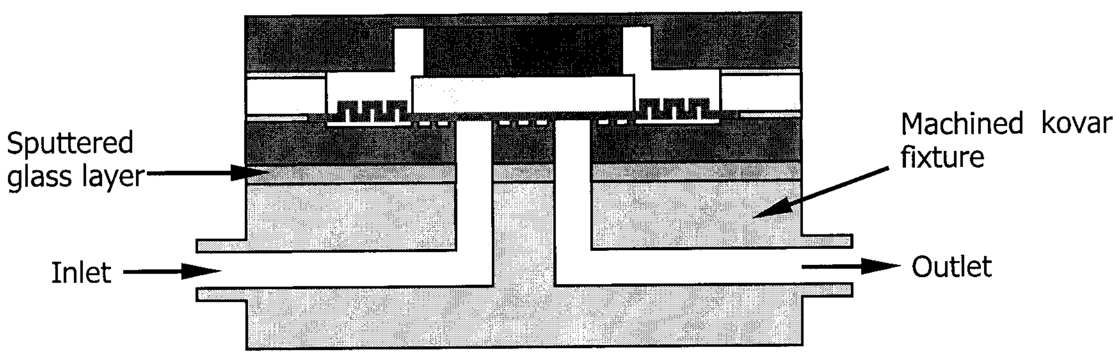

Figure 5. Kovar, silicon, and glass anodic bonding forms the fixture for testing leak and flow rate of the micro-valve prototype.

CONCLUSION

To address the needs for space application, a micro valve program was initiated at JPL. We are now at the stage of producing the first prototype valves for testing. We have also begun the development of the test setup that can be modified to accommodate various types of packaged and unpackaged microvalves.

ACKNOWLEGEMENT

The research in this paper was performed by the Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration, Office of Space Science.

REFERENCES

[1] P. W. Barth, "Silicon Microvalves for Gas Flow Control," *The 8th International Conference on Solid State Sensors and Actuators, and Eurosensors IX,* Stockholm, Sweden, June 25–29, 1995, pp 276–279.

[2] M. Esashi, S. Shoji and A. Nakano, "Normally close microvalve and micropump fabricated on a silicon wafer," *Proc., IEEE Micro Electro Mech. Syst. Workshop*, Salt Lake City, UT, February 20–22, 1989, pp 29–34.

[3] T. Ohnstein, T. Fukiura, J. Ridley, and U. Boone, "Micromachined silicon microvalve," *Proc., IEEE Micro Electro Mech. Syst. Workshop*, Napa Valley, CA, February 11–14, 1990, pp. 95–98.

[4] Michael A. Huff and Martin A. Schmidt, "Fabrication, packaging, and testing of a wafer-bonded microvalve," *Tech. Dig., IEEE Solid-State Sensor and Actuator Workshop,* Hilton Head Island, SC, June 22–25, 1992, pp. 194–197.

[5] B. Wagner, H. J. Quenzer, S. Hoerschelmann, T. Lisec, and M. Juerss, "Bistable microvalve with pneumatically coupled membranes," *Proc., IEEE Micro Electro Mech. Syst. Workshop,* San Diego, CA, February 11–15, 1996, pp. 384–388.

[6] Inductively-Coupled Plasma (ICP) silicon etcher by *Surface Technology System.*